DEVELOPMENT OF GAS GAP HEAT SWITCH ACTUATOR FOR THE PLANCK SORPTION CRYOCOOLER *

M. Prina,[1] P. Bhandari,[2] R. C. Bowman Jr.,[2] C. G. Paine,[2] L. A. Wade [2]

[1] Politecnico di Milano
Milano, Italy
[2] Jet Propulsion Laboratory
Pasadena, CA, 91109, USA.

ABSTRACT

A heat switch has been designed and characterized for the thermal control of the compressor beds in ESA Planck Surveyor 20 K sorption cryocooler. The heat switch has been designed to minimize the overall cryocooler power and to maximize the stability of the cold tip temperature, both of which are strongly affected by the performance of the gas-gap heat switch actuator. The gas gap thermal switching is obtained by varying the pressure of hydrogen a closed volume defined by the two surfaces to be thermally connected or isolated. Hydrogen pressure within this volume is controlled by thermally varying the equilibrium hydrogen content of a hydriding metal. Switching characteristics are determined by the mechanical and thermal properties of the switch actuator containing the hydriding material to give a heat conduction ratio of over 1000 between the ON and OFF states. We present the general principles of gas gap heat switches that impact their performances for the Planck cryocooler, develop two figures of merit relevant to this application, and present initial characterization results of switches using uranium or ZrNi as the hydriding material.

INTRODUCTION

An 18 K continuous-cycle sorption cryocooler is being developed[1,2] for the ESA Planck mission[3], which will map the anisotropy of the cosmic microwave background.

This cooler will produce liquid hydrogen by a closed-cycle Joule-Thomson expansion of gas compressed and circulated using metal hydride sorbent beds in the compressor assembly. The compressor assembly will be located on the spacecraft bus and is attached to radiators for passive cooling to 280 K in order to provide a heat sink for cooling the sorbent beds to their absorption temperature and rejecting the heat of absorption. Each compressor bed will be provided with a gas gap heat switch for thermal coupling or decoupling of the sorbent material from the 280 K radiator. While gas-gap switches have been used previously on cryocoolers[4,5], the operating conditions and power limitations for the Planck sorption coolers require modified design and performance. In this report we concentrate on the development and behavior of the gas-gap actuators for the Planck mission; the overall behavior of the sorbent compressor elements will be reported elsewhere.

HEAT SWITCH DESCRIPTION

The gas gap heat switch is used to thermally connect or disconnect two objects, by filling the gap between the surfaces of the objects with gas at a pressure P_{ON}, or evacuating the gap to a pressure P_{OFF}. The pressure in the gap determines the heat transfer, as indicated in Figure 1. The pressure P_{ON} will be close to P_2 , and P_{OFF} will be lower than P_1.

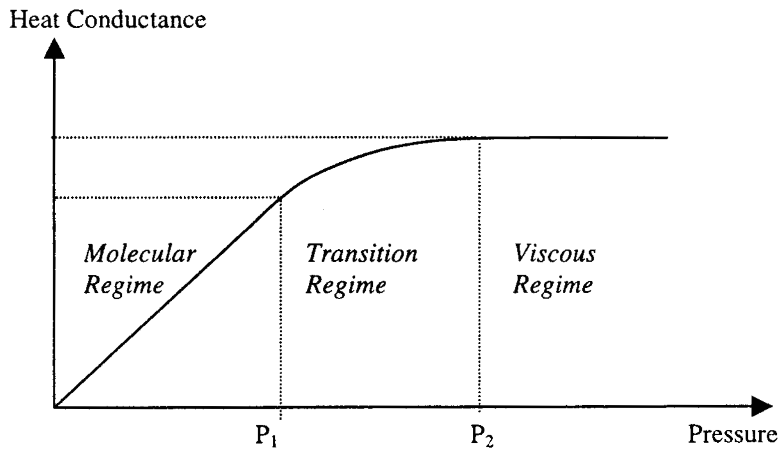


Figure 1: Heat conductance versus pressure.

Optimal heat switching requires a high gas thermal conductivity and an actuator to reversibly insert and extract the gas. Hydrogen and hydriding metals have been selected as the approach for this gas-gap switch actuator.

OPERATION CONCEPT OF THE HEAT SWITCH

The hypotheses assumed in the heat switch design are:

- Hydrogen as ideal gas

- Switch assembly is isothermal. The thermal gradient is only in the tube connecting the actuator to the compressor bed.
- The tube is considered only as a conductance and not as an additional thermal mass.
- Infinite kinetic speeds of the H_2 absorption desorption reactions.
- The heater power supplied during the ON state is constant and equivalent to the switch ON state equilibrium power (see Eq.(2)).
- The switching operations are synchronous with the compressor bed operations
- The heat of re-absorption is negligible.
- The heater has a thermal mass equal to the shell mass (hydrides, shell and filter)

The general configuration of a gas gap heat switch is shown in Figure 2.

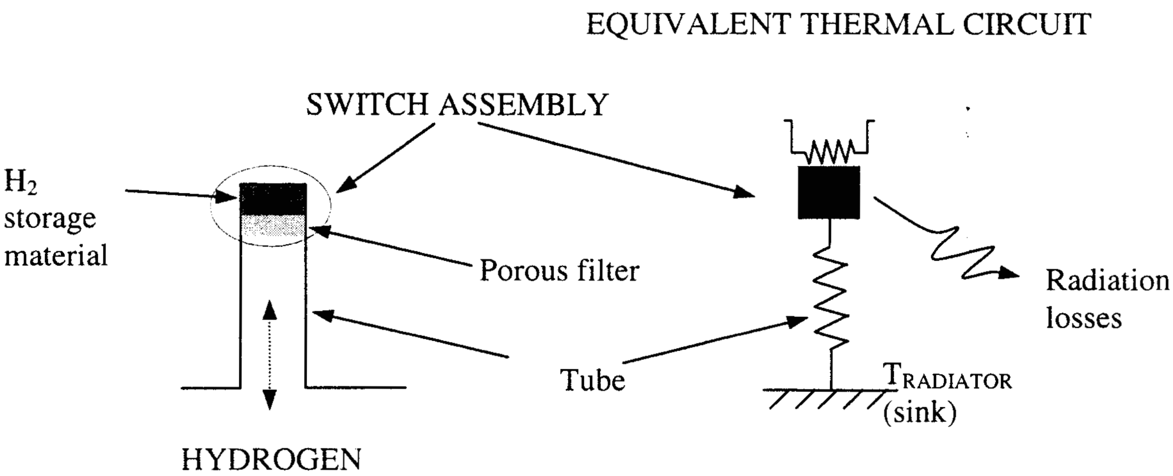


Figure 2: Schematic and equivalent thermal circuit of the gas gap heat switch.

The relations describing the switch actuator thermal behavior according to the previous hypothesis are:

- thermal switching of the assembly

$$(mcp)_{SwitchAss.}\frac{dT_{SwitchAss.}}{dt} = Power - G(T_{SwitchAss} - T_{Sink}) - \varepsilon\sigma_0 A_{SwitchAss}(T^4_{SwitchAss} - T^4_{Sink}) \qquad [1]$$

G is the heat conductance of the stainless steel tube (length L and diameter D)
The previous expression, solved for steady state condition, provides the value of the $Power_{Switch}$ required to maintain the switch in the ON state:

$$Power_{Switch} = G(T_{High} - T_{Sink}) + \varepsilon\sigma_0 A_{SwitchAss.}(T^4_{High} - T^4_{Sink}) \qquad [2]$$

- Van't Hoff equation for the hydride pressure range.

$$\log P_{Assembly} = B - \frac{A}{T_{Assembly}} \qquad [3]$$

The constants A and B depend on the H_2 storage material and define the pressure (P) produced within the gas gap assembly.

- Flow resistance from porous filter

Pressure drop across the porous filter is considered using the equations:

$$\dot{n} = \frac{V_{Gap}}{RT_{Gap}}\left(\frac{dP_{Gap}}{dt}\right) \qquad [4]$$

And

$$\left(P_{Gap} - P_{Assembly}\right) = \frac{4\dot{n}M_{H_2}RT_{Assembly}}{\pi D^2\sqrt{\frac{T_{Assembly}}{294}}\,\overline{C}\,\frac{t_{Filter}}{t_{sample}}} \qquad [5]$$

Where D is the diameter of the porous filter (the same of the tube) and t_{sample} is the thickness of a the test filter that at 294 K gave the flow conductance C.

- Thermal conductance as a function of pressure[6]

$$G = Area\frac{K_{H_2}}{Gap + (9\gamma - 5)\frac{2-\alpha_{Tot}}{\alpha_{Tot}}L} \qquad [6]$$

Where:
γ is the ratio of specific heat at constant pressure to that at constant volume for hydrogen at the temperature of the gas.
Gap is the distance between the two surfaces.
L is the mean free path of hydrogen at a pressure P_{Gap} and at a temperature T_{Gap}.
Area is the area of the surfaces on the gap.
α_{Tot} is the global accommodation coefficient defined as

$$\alpha_{tot} = \frac{\alpha_{comp.unit}\cdot\alpha_{radiator}}{\alpha_{comp.unit} + \alpha_{radiator} - \alpha_{comp.unit}\cdot\alpha_{radiatar}} \qquad [7]$$

and then individual α are accommodation coefficient for the two surfaces, a measure of the efficiency of thermal transport between the surface and the gas: $0 < \alpha < 1$.

SYSTEM REQUIREMENTS

Gas-gap switches are incorporated in the Planck sorption compressors to allow the sorbent material (a $LaNi_{4.8}Sn_{0.2}$ hydride) to be isolated from its surroundings while heated to approximately 480 K for desorption of stored hydrogen, then to cool the sorbent material to approximately 280 K for re-absorption of the hydrogen refrigerant fluid into the rare earth alloy material. The sorbent portion of each compressor element is cycled through this temperature range once in approximately 4000 seconds. Constraints on available power and radiator size impose performance requirements on the gas-gap switch actuator. The actuator must

1) supply gas at sufficient pressure that the ON-state conductance is adequate for cooling of a sorption bed to the temperature at which re-adsorption occurs, and rejection of the heat of absorption at that temperature
2) extract gas to low enough pressure that OFF-state residual gas conduction is tolerable while the sorbent material is at high temperature
3) perform both transitions between ON- and OFF-states quickly enough that there is adequate time to cool a bed for re-absorption, and time to heat a bed for desorption.

Consideration of the Planck operational conditions have indicated that it is the switching OFF-to-ON, and the OFF-state steady-state conductance at high temperature, which are the most stringent performance requirements for this application. From this, and from constraints on total system electrical power, we find it useful to express the behavior of the switch actuators in terms of two figures of merit, as discussed below.

Figure Of Merit: OFF-ON Switching Margin

As is seen in Figure 1, there is a limiting conductance for a gas gap; even if the gas-gap became conductive instantaneously, the time to transfer heat across the switch is finite. For a real actuator, which requires some time to change the conductance within the gas-gap, the time required to transfer heat is related to the gas-gap pressure as a function of time. In the evaluation of designs presented below, the Figure of Merit "Margin" is the fractional enthalpy which could be transferred across the switch within the allowed time interval, in excess of the requirements for the Planck system design:

$$\text{Margin} = \frac{(mcp) - (mcp)_{Comp.unit}}{(mcp)_{Comp.unit}}$$

where mCp is the maximum enthalpy transferable by a given switch design, and $mCp_{comp\ unit}$ is the requirement for the PLANCK system design.

Figure Of Merit: Total Power

The gas-gap switch actuators are controlled via heaters, which dissipate electrical power. The primary sorption compressor storage material also employs electrical heaters for cycling the working fluid; gas remaining in the gas-gap switch during the actuator OFF-state can increase this power requirement. The total system electrical power requirement is dominated by the sum of these two contributions. It is this electrical power which we wish to minimize through design of the actuator.

It is clear that these two figures of merit give rise to conflicting design requirements; minimizing the switching time is easily done by increasing thermal conduction between the actuator storage material and its thermal sink, but this increases power dissipation required to heat the actuator. Similarly, a choice of hydrogen storage material that yields lowest pressure at low temperature (OFF-state) will require higher heater power to maintain adequate pressure at high temperature (in the ON-state). We have examined the effects of configuration and material selection on the overall system performance, relative to the above figures of merit; these considerations and results are presented next.

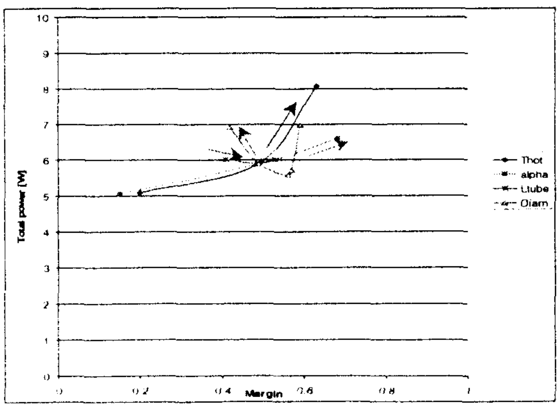
GAS-GAP ACTUATOR DESIGN

We have selected two materials, ZrNi and Uranium, for evaluation as hydrogen-storage materials for gas-gap switch actuators. We have parameterized the response of these actuators in terms of the material properties, thermal characteristics of the actuator design, and gas-gap switch behavior. We have constructed switch actuators utilizing these materials based upon the results of the parameterization; these actuators are now undergoing characterization.

The physical design of the switch actuator is as indicated in Figure 4. A tube of 12.7 mm OD, 0.15 mm wall thickness, 316L stainless steel tubing provides thermal isolation between a thermal sink (which is part of the gas-gap switch) and the switch actuator containing the hydriding material; 0.2-0.50 grams of hydriding material was encapsulated in the actuator, which included a stainless steel filter and an external heating element. With these parameters fixed, the thermal mass of the actuator calculated, and the behavior of the gas-gap switch for varying gas pressure calculated, we examined the effect upon gas-gap performance due to variation in four parameters associated with the actuator design and gas-gap characteristics:

- the temperature to which the actuator must be raised, to produce the gas-gap ON condition of >15 torr gas pressure at 300 K (~470 K for ZrNi, ~560 K for Uranium);
- the length of the thermal isolation tube, treated as a free parameter;
- the diameter of the isolation tube (including changes in gas flow related to the change in restriction due to changing diameter of the filter);
- the accomodation coefficient of the walls of the gas-gap (which is influenced by other system constraints that will not be addressed here).

The results of variation about a design point, relative to the Figures of Merit detailed above, are indicated in Figure 3a and 3b, for the two materials under consideration. Variation of the design parameters in this manner has allowed us to perform tradeoffs amongst the competing figures of merit while retaining reasonable physical and thermal designs for the gas-gap actuator.



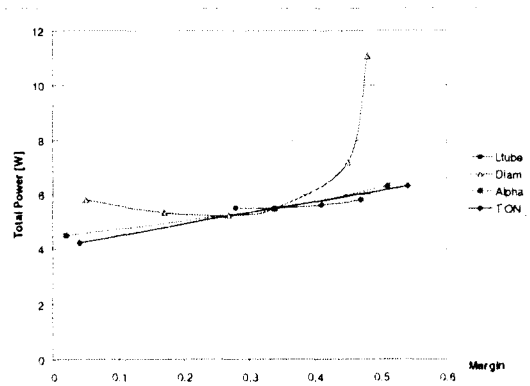


Figure 3. Variations in the gas gap switch performance about the design points for the ZrNi (a) and U (a) actuator hydride.

TEMPERATURE CYCLING TESTS

Prototype versions of the gas gap switch configuration from Figure 1 have been fabricated to permit testing in the laboratory of the operational parameters and performance of the hydride materials during extended thermal cycling.

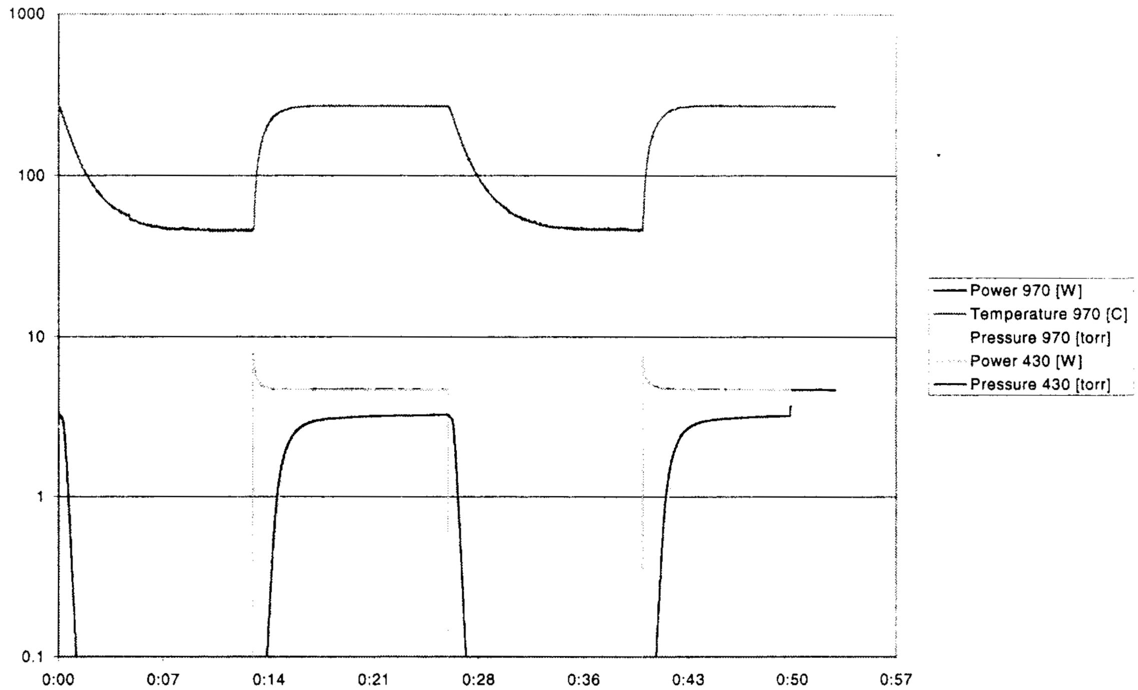


Figure 4. Pressure, Power, and Temperature profiles of gas gap switch containing ZrNi hydride observed during cycles numbers 1 and 1414.

Heat switches have been built containing ZrNi and uranium metal with the hydride encapsulated in the 126 mm^3 volume between the cap and porous filter. The hydride sorbent was inserted as a bulk metal into the volume that was sealed by e-beam welding the cap, the filter and the tube together. After assembly of the heat switches and activation of the sorbent, the hydride was charged with the appropriate quantity of hydrogen before starting the cycling experiments. The response for temperature and pressure during the initial cycles agreed closely with the behavior predicted by our analyses.

The effect of continued cycling on a ZrNi actuator is shown in Figure 4, which compares the initial and 1414^{th} cycles. No changes in either the input power or the temperature profile are seen. The ON state pressure values have remained constant, but rate of pressure decrease below 10 mTorr is somewhat slower during the 1414^{th} cycle. The source of this latter behavior is currently unknown and will be subject of further study as the cycling is continued.

During the initial cycles with the uranium gas gap switch, the actuator was heated to 558 K to produce an ON state pressure of ~15 Torr. However, there were problems with attachment of the heater after a few cycles. After several modifications in heater attachment method and the maximum temperature, a stable configuration was found where a maximum temperature of 513 K was used to produce a 4.2 Torr ON state pressure. No further problems have been detected during the next several hundred cycles. As an example, the parameters obtained during the cycles 430 and 970 are compared in Figure 5.

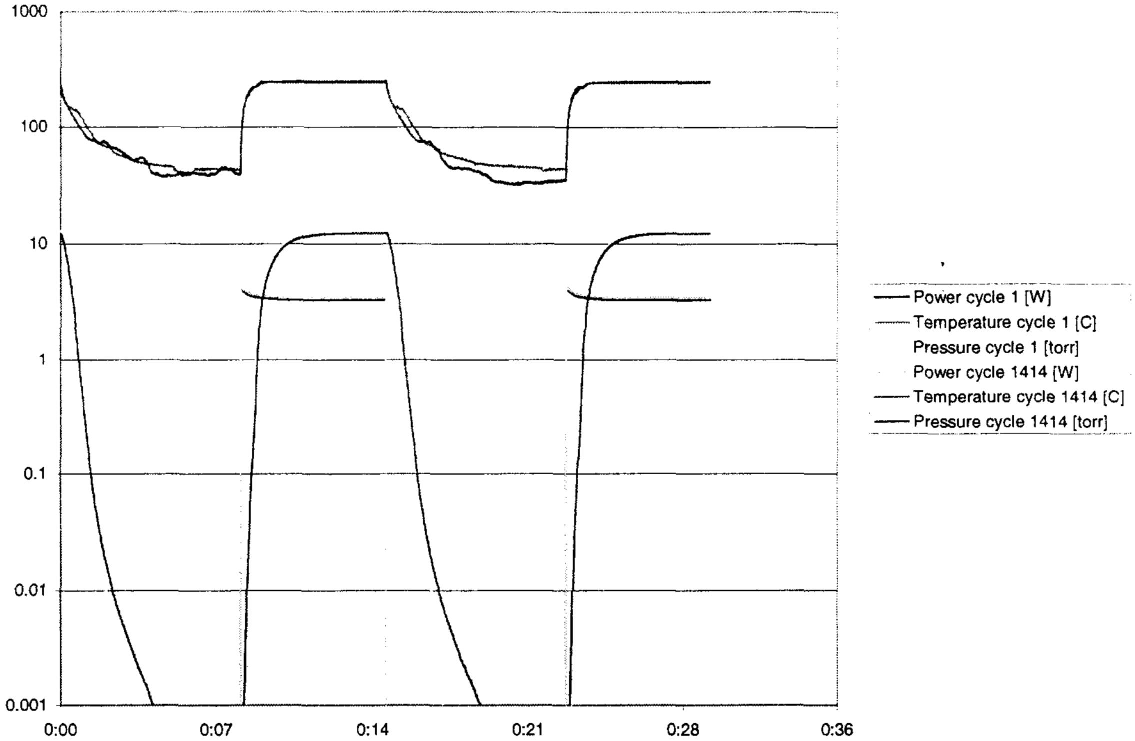


Figure 5. Pressure, Power, and Temperature profiles of gas gap switch containing uranium hydride observed for cycles numbers 430 and 970.

During these cycles, the power and temperature profiles are identical with only a small decrease in the pressure.

CONCLUSIONS

Operational requirements have been derived for the gas gap heat switch according to the present operational behavior of the Planck sorption cooler. Realistic mechanical designs for the candidate actuator materials ZrNi and U have been analyzed in terms of variations in design options. The designed configurations have be built and tested. Initial results validate the model predictions with respect to input power requirements and time constants for the turning the switches on and off. Little degradation in the behavior of the actuator hydrides have been seen after ~1000 cycles. Future work involves long term cycling of the actuators as well as assessment of the heat transfer characteristics of the Planck compressor sorbent bed. These results will be used to refine the design of the gas gap switch and selection of the optimal actuator hydride.

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